CFD SIMULATION OF DIFFUSION OF HYDROGEN LEAKAGE CAUSED BY FUEL CELL VEHICLE ACCIDENT IN TUNNEL, UNDERGROUND PARKING LOT AND MULTISTORY PARKING GARAGE

Shinji Mukai
Jinji Suzuki
Hiroyuki Mitsuishi
Kenshun Oyakawa
Shogo Watanabe
Japan Automobile Research Institute
Japan
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ABSTRACT

Hydrogen fuel cell vehicles are expected to come into widespread use in the near future. It is therefore important to predict whether risks from hydrogen leaked caused by accident in semi-enclosed area can be avoided. In this study, CFD simulation was carried out for hydrogen leakage in typical tunnels, underground parking lot, and multistory parking garage. Simulation scenarios were as follows. The hydrogen leak rate was chosen to be the equivalent energy of allowable gasoline fuel leak in a vehicle collision test, as prescribed in FMVSS301. The ventilation rate was zero for the case of tunnels, and air exchange rate was zero or ten times per hour for underground parking lots. The analytical periods were thirty minutes for all cases. It can be said that the area of flammable mixture was limited that close to the hydrogen leaking vehicle even when there was no ventilation and become smaller when the ventilation exists. The results would therefore indicate that safety was maintained in cases of hydrogen leakage in the semi-enclosed areas even with existing equipment.

INTRODUCTION

Recent years have seen an advance in global warming due to carbon dioxide and other emissions, and various approaches are being investigated to suppress these emissions. One approach is to promote to cleaner emissions from automobiles, which use mainly fossil fuels. Another approach is the development of fuel cell vehicles, which use hydrogen instead of fossil fuels as an energy source. Fuel cell vehicles have attracted much attention as clean cars with no harmful emission gases. Today, various public and private organizations are conducting driving tests on public roads of fuel cell vehicles produced by major automakers in each country, and collecting data to be used in developing these vehicles for the commercial market. To promote the use of these vehicles, Japan is today reviewing its relevant laws and regulations. Before regulations can be revised, however, it is necessary to investigate the safety of fuel cell vehicles during accidents.

In the present study, tunnels, an underground parking lot, and a multistory parking garage were chosen as semi-enclosed spaces where fuel cell vehicles would be driven and stored. Safety of hydrogen leakage in such spaces was investigated. The purpose of the present experiment was to predict whether leaking hydrogen would pose a danger to the selected facilities. Specifically, we wanted to investigate the diffusion of leaking hydrogen in semi-enclosed spaces, where it accumulates in those spaces, the behavior in which it accumulates, and the region above the lower flammable limit.

SUBJECTS OF ANALYSIS

Tunnel

Two tunnel shapes were chosen for the present study. To simulate a long tunnel we selected a cross-sectional configuration with a 2% uniform rising and downing longitudinal slope, and to simulate an underwater tunnel one with a 5% uniform trough longitudinal slope [1]. The space for analysis was limited to a length of 50 m. Tunnel width was 10 m, and tunnel height was 7 m for the long model tunnel and 4.5 m for the underwater model tunnel. Both model tunnels were considered to have one way direction road with 2 lanes. The hydrogen leakage was from a fuel cell vehicle driving in the tunnel, resulting from

a collision or other accident. The leak occurred in the middle of the tunnel with the vehicle stopped. The vehicle with the hydrogen leak was in the passing lane, followed by 4 other vehicles. Thus, there was a total of 5 vehicles in the tunnel. This calculation was done under a condition of no ventilation. Figure 1 shows a cross-section of the 2 model tunnels.

Analyses were done for the following 3 cases.

  Case T-1: Long model tunnel

  Case T-2: Underwater model tunnel
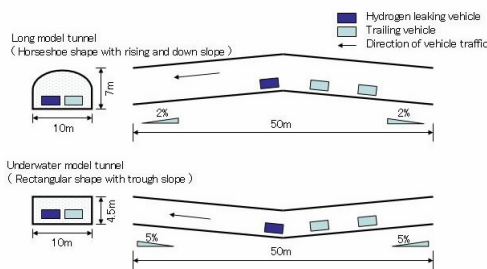
  Case T-3: Long model tunnel (length 200 m)

Figure 1.   Tunnel configuration.

Underground Parking Lot

A general self-parking underground parking lot [2] was adopted as the configuration for analysis. One section from among all the areas of the parking lot was taken as the area for analysis. This section was one with 9 vehicles each in 2 rows, a total floor area of 480 m^2 and ventilation equipment. This area was subject to the requirement for underground parking lots with a floor area of greater than 500 m^2 to have air exchange at least 10 times/h (Fire Defense Law enactment order).

The parking lot had air duct to the road, and was equipped with emissions ducts in the parking areas. And the number of air exchanges per hour was set at 0 times/h (assuming equipment failure) and 10 times/h. The hydrogen-leaking vehicle was located in the middle of the 9 vehicles; in other words, some distance from the entrance and exit. Figure 2 shows the arrangement of the vehicles in the underground parking lot.

Analyses were done for the following 3 cases.

  Case U-1: Air exchange 10 times/h

  Case U-2: No air exchange

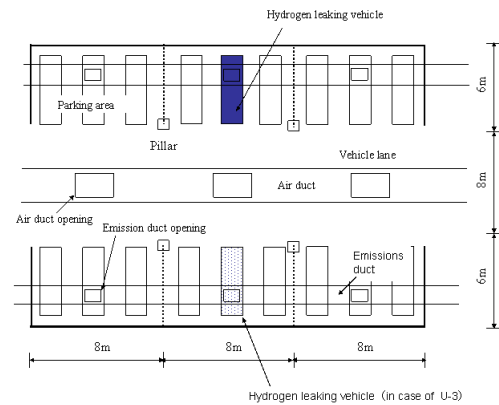 Case U-3: No air exchange (2 leaking vehicles)

Figure 2.   Configuration of underground parking lot.

Multistory Parking Garage

The configuration adopted for analysis was an elevator parking tower [3], which are commonly seen in Japan in recent years (432 in operation in 2001). The frontage of the parking garage is 6.5 m x 7.5 m in depth x 30 m in height. The garage holds 24 vehicles (12 vehicles x 2 rows). Vehicles enter and exit this parking garage through a ground floor opening that directly faces the outside atmosphere, and there is an emissions louver (ventilation hole) near the ceiling. The location of the vehicle leaking hydrogen was set as an analysis parameter, with the 2 locations of the lowest and the second from highest positions. Figure 3 shows the location of the vehicles in the multistory parking garage.

The following 3 cases were selected for analysis.

  Case M-1: Leaking vehicle on the lowest level

  Case M-2: Leaking vehicle on the second from highest level

  Case M-3: Leaking vehicle on the lowest and the second to highest levels (2 leaking vehicles)
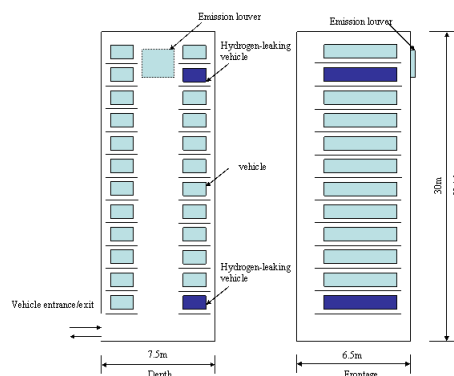

Figure 3. Schematic representation of multistory parking garage.

NUMERICAL SIMULATION METHOD

Simulation Scenario

The number of vehicles leaking hydrogen was set at 1 or 2 for the tunnel, underground parking lot, and multistory parking garage. The vehicles were given a linear configuration with dimensions of 4.7 m x 1.8 m x 1.7 m. The hydrogen leak rate was set at 133 L/min (20°C), which is the energy equivalent of the allowable gasoline leak and prescribed in the "Fuel system integrity" of U.S. federal automobile safety standard FMVSS301. The hydrogen leak rate was considered to be a constant flow during the release period of 30 minutes within the given space. The leaking portion of the vehicle was the boundary surface with a rate of 0.887 m/s, and the leak direction was horizontal from the rear of the vehicle. The leak hole was a square with sides of 0.05 m. The hydrogen did not enter the vehicle passenger compartment.

In an actual fuel cell vehicle, hydrogen gas leaking from the fuel system is sensed and the fuel supply is cut off with an interlock or some other device. Thus, an actual fuel leak can be expected to continue only for several minutes. The present simulation is therefore for a situation more dangerous than an actual occurrence.

Calculation Model

Calculations were done with the general flow modeling software program STAR-CD, using the following calculation model. The governing equation for flow was taken to be a 3-dimensional nonsteady Navier-Stokes equation (continuous, momentum; gravity was considered), and a preservation formula was applied to the concentration site with hydrogen and air shown as mass fractions. The working fluids were standard air and standard hydrogen of 20 °C, in noncompressed flows. The temperature was constant. Table 1 shows the property values used. The turbulence model and other factors used in the calculations were as follows.
·Turbulence model: Standard k-ε model (high Reynold's number, combined with wall functions)
·Turbulence intensity: 10% of main flow at leaking hole
·Turbulence length scale: 5% of leaking hole diameter
·Differencing scheme: third order scheme for convection term (QUICK: Quadratic upstream interpolation of convective kinematics)

·Turbulence Schmidt number: 0.9
·Time interval: 0.2 sec
·Solution method: PISO (Pressure Implicit Split Operator)

Table 1.
Property values of hydrogen and air used

Air	Density	1.204	[kg/m³]
	Kinematic viscosity	1.50E-05	[m²/s]
Hydrogen	Density	8.38E-02	[kg/m³]
	kinematic viscosity	1.05E-04	[m²/s]
Mutual diffusion coefficient[4]		7.77E-05	[m²/s]

Mesh

Unstructured mesh (hexahedral mesh) was used for all cases, and the mesh number was approximately 200,000 points in cases of tunnel and multistory parking garage, and was approximately 400,000 points for the case of underground parking lot. A half-model was used for the underground parking lot because of its symmetrical configuration.
The meshes for the tunnel, underground parking lot, and multistory parking garage are shown in Figs. 4, 5, and 6, respectively.
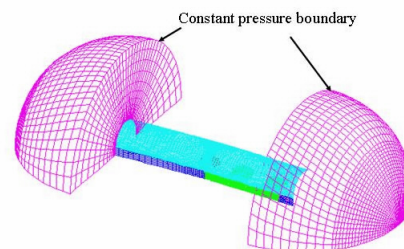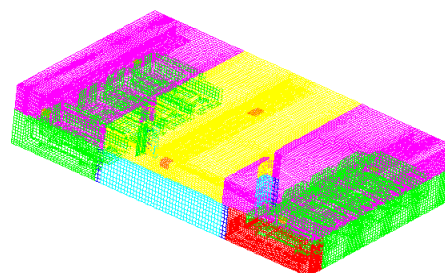

Figure 4. Tunnel mesh (long model tunnel)

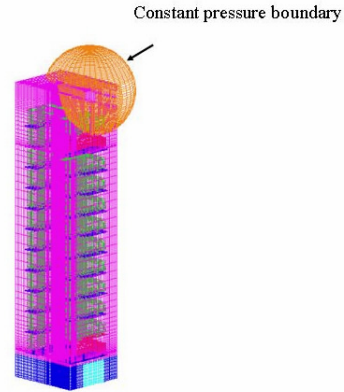**Figure 5. Underground parking lot mesh (half model)**

Figure 6. Multistory parking garage mesh

RESULTS AND DISCUSSION

In all cases, the changes with time in hydrogen concentration are shown in a representative cross-section including the hydrogen-leaking vehicle and so on. The hydrogen concentration contour is shown in a total of 14 colors against a blue background. The region above lower flammable limit for hydrogen in air (4 volume %) is shown in red.

Tunnel

Two representative cross-sections including the hydrogen-leaking vehicle for tunnel results are shown in Figure 7.
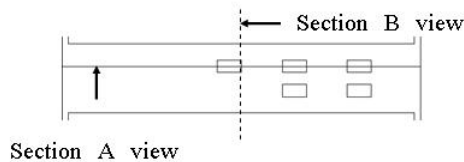

Figure 7. Cross section showing tunnel results
 (Section A: from side; Section B: from rear).

Effects of cross-sectional configuration of tunnel

Figure 8 shows the leaked hydrogen distribution within the long model tunnel simulation in Case T-1.
Hydrogen leaking toward the rear from the back of the vehicle has a much lower density than air, so it immediately flows upward. After the leaking hydrogen rises and reaches the ceiling of the tunnel, it mainly disperses in the longitudinal direction. At the point when it reaches the ceiling, the hydrogen concentration is already

below the lower flammable limit. The region above the lower flammable limit is restricted to a small area around the source of the hydrogen leak, up to a height of approximately 3 m.
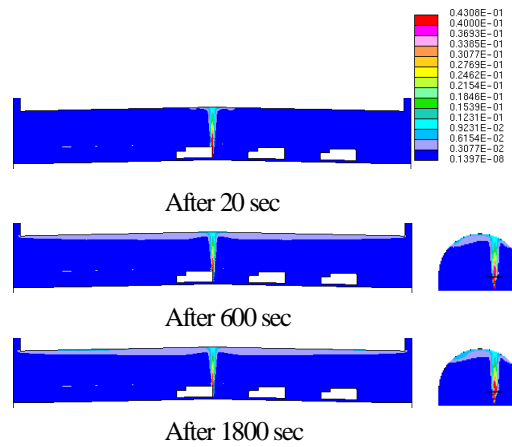

After 20 sec

After 600 sec

After 1800 sec

Figure 8. Hydrogen distribution in long model tunnel (left: Section A; right, Section B).

Next, Fig. 9 shows the hydrogen dispersion in Case T-2 simulating the underwater model tunnel. In this case, the upper wall slope of tunnel is upward toward the tunnel before and behind, so the time until the diluted hydrogen reaches the tunnel end is shorter than in Case T-1. This is because the buoyant force of the hydrogen acts in the direction of easy diffusion. After the diluted hydrogen reaches the tunnel end, the hydrogen concentration distribution remains unchanged and constant. Just as with the long model tunnel, the region above the lower flammable limit is restricted to a small area close to the hydrogen leak.
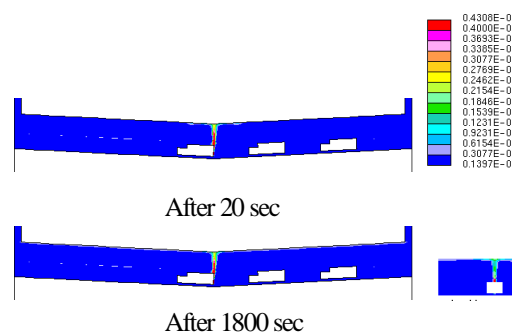

After 20 sec

After 1800 sec

Figure 9. Hydrogen distribution in underwater model tunnel (left: Section A; right, Section B)

Influence of tunnel length

To investigate the influence of tunnel length for the long model tunnel, calculations were made for a length of 200 m (Case T-3). The mesh number was approximately

300,000 points. The results are shown in Fig. 10. Because of the long tunnel length, the height of the exits at either end of the tunnel is shorter than in Case U-1, and a thick layer of diluted hydrogen accumulates at the tunnel ceiling. However, as in Case U-1 the region above the lower flammable limit is restricted to a small area immediately next to the hydrogen leak.
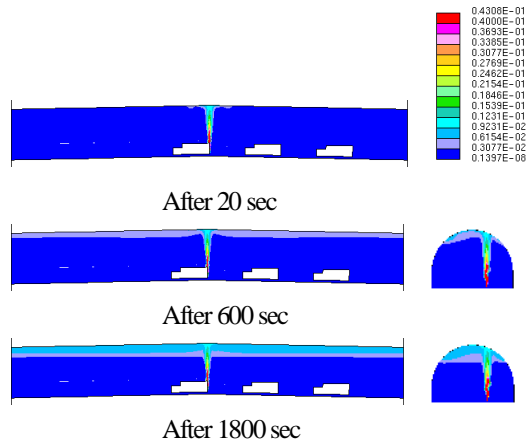

After 20 sec

After 600 sec

After 1800 sec

Figure 10. Hydrogen distribution in long model tunnel with length of 200 m (50 m section is magnified and shown; left: Section A; right, Section B).

Longer tunnel length is considered to more closely resemble existing tunnels, and there was a greater tendency for accumulation with a tunnel length of 200 m. However, in the case of hydrogen leaks below the allowable level in collisions, it may be possible to enough confirm the effects due to differences in tunnel cross-sectional shape even with a tunnel length of 50 m.

Underground Parking Lot

Two representative cross-sections for underground parking lot results are shown in Figure 11. These are cross sections including the hydrogen-leaking vehicle, and near the ceiling.
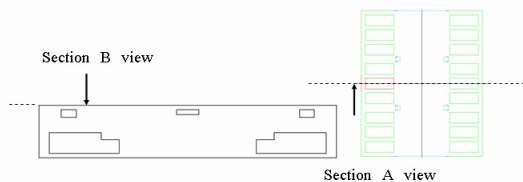

Figure 11. Cross section showing underground parking lot results (left: cross section including hydrogen-leaking vehicle from side (Section A); right: near ceiling at 3.5 m from above (Section B)).

Effects of air exchanges

Firstly, the hydrogen concentration distribution when there is air exchange (Case U-1) is shown in Fig. 12. The flow of hydrogen leaking backward from the rear of the vehicle is deflected upward immediately since hydrogen has a much lower density than air, and rises to the ceiling where it gradually diffuses in a radial pattern. The leaking hydrogen maintains a concentration above the lower flammable limit until it reaches the ceiling at a height of 3.5 m, where it diffuses and becomes diluted to below the lower flammable limit. A portion of the diffused hydrogen is partly drawn into the emissions duct, so almost none of region of diluted hydrogen (0.3 volume%: gray) reaches the vehicle entrance and exit. Moreover, the hydrogen that flows into the emissions duct is below the lower flammable limit. The hydrogen flowing out through the parking lot emissions duct is proportional to that leaking from the vehicle, and it takes about 900 sec to reach a steady state. The region above the lower flammable limit is restricted to a small area directly behind the hydrogen leak.
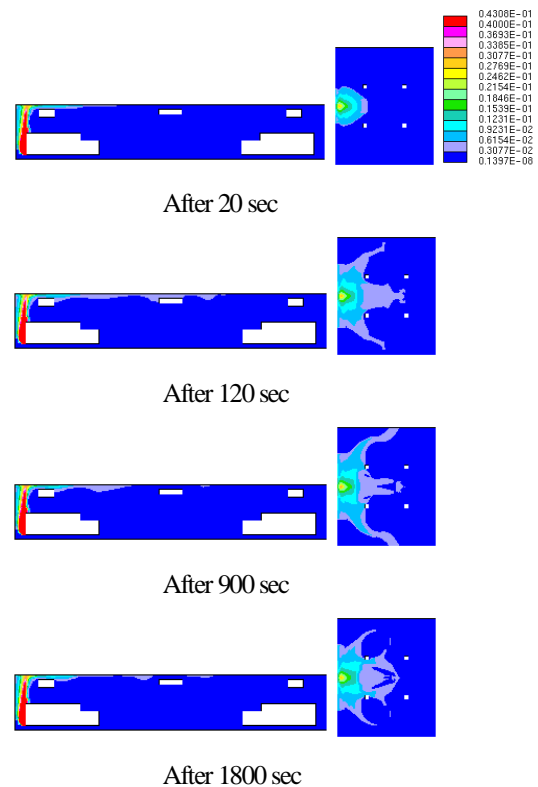

After 20 sec

After 120 sec

After 900 sec

After 1800 sec

Figure 12. Hydrogen distribution in underground parking lot (Case U-1; left: Section A; right, Section B).

Next, Figure 13 shows the hydrogen concentration distribution when there is no air exchange (Case U-2). The flow of hydrogen leaking backward from the rear of the

vehicle is immediately deflected upward because of its low density. It rises to the ceiling and gradually diffuses in a radial pattern after slowly colliding with the wall. That is the same as Case U-1. The region of diluted hydrogen (0.3 volume %) reaches the parking lot entrance and exit about 120 s (2 min) after the start of the leak. The flow out from the parking lot entrance and exit is proportional to the hydrogen leak from the vehicle, and hydrogen distribution condition in area is reached in a steady state after about 1200 s. Even with no ventilation, the region above the lower flammable limit is restricted to a small area immediately next to the hydrogen leak.
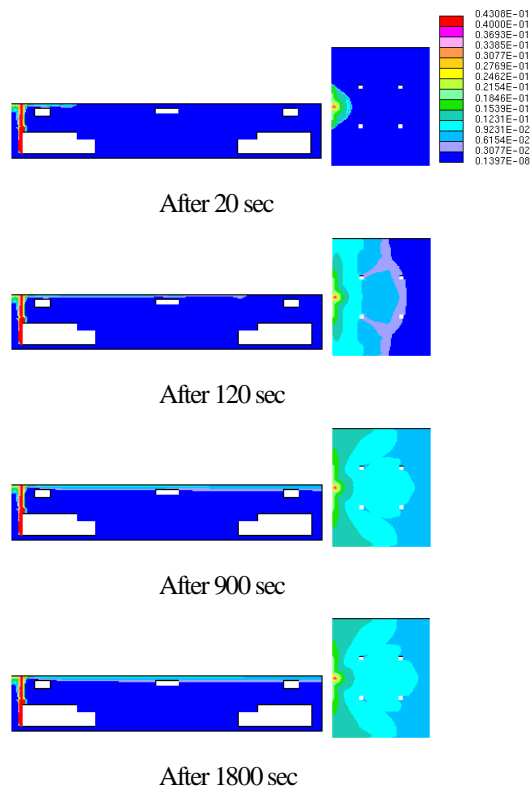

After 20 sec

After 120 sec

After 900 sec

After 1800 sec

Figure 13. Hydrogen distribution of underground parking lot (Case U-2; left: Section A; right, Section B)

Figure 15 shows the changes with time of hydrogen concentration inside the parking lot at various points from the results of Cases U-1 and U-2. Measurements were taken at 3 points just below the ceiling: directly above the leaking vehicle, on the opposite side from the leaking vehicle, and at the entrance and exit on the vehicle side. The hydrogen concentration was lower at all 3 points in the simulation with air exchange than in that without air exchange. The hydrogen concentration at the entrance and exit was decreased from about 1.4 % to below 0.05 %. The hydrogen concentration directly above the hydrogen leaking vehicle decreased from 4 volume % to below the
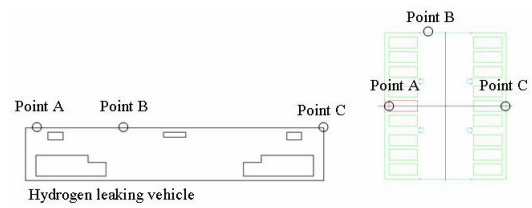
flammable limit.

Figure 14. Data collection points on ceiling in underground parking lot (A: directly above hydrogen-leaking vehicle; B: vehicle lane (same side as hydrogen-leaking vehicle); C: opposite from hydrogen-leaking vehicle).
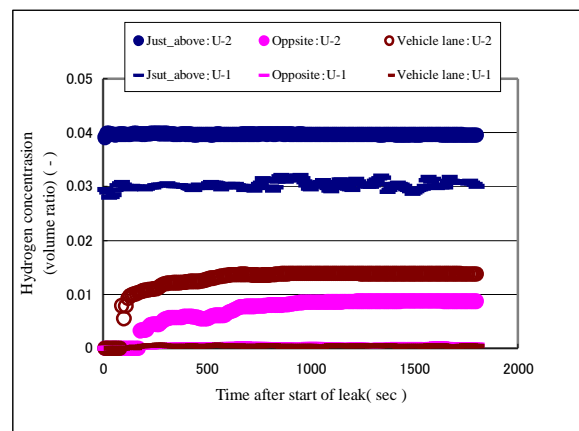

Figure 15. Changes with time in hydrogen concentration at each point on ceiling in underground parking lot (Cases U-1 and U-2)

Influence of number of leaking vehicle (1 or 2)

Figure 16 shows results of the hydrogen concentration distribution with 2 leaking vehicles under no air exchange condition. The region of diluted hydrogen concentration near the ceiling is a little thicker because the number of leaking vehicles was increased from 1 to 2. However, the region of hydrogen above lower flammable limit is restricted to around the hydrogen leaks and a very small area on the ceiling above the hydrogen leaks.
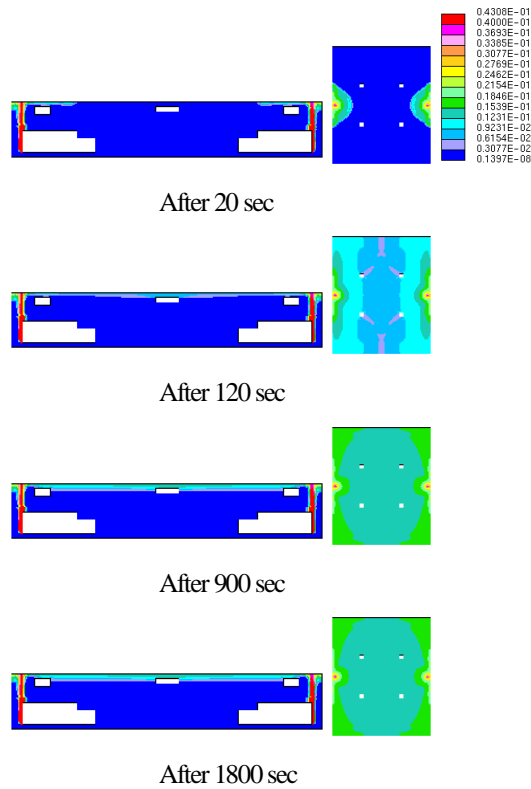
After 20 sec

After 120 sec

After 900 sec

After 1800 sec

Figure 16. Hydrogen distribution in underground parking lot (Case U-3; left: Section A; right, Section B).

Multistory Parking Garage

Figure 17 shows the cross-sectional positions from the results for the multistory parking garage.
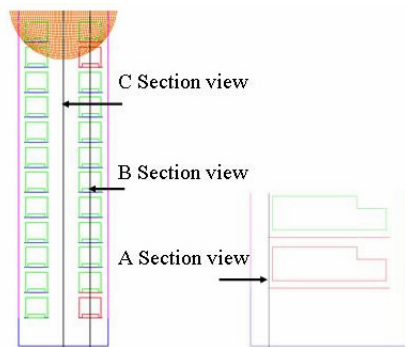

Figure 17. Cross section showing results for multistory parking garage (A: cross section including rear edge of pallet; B: cross section including hydrogen-leaking vehicle; C: cross section of center space in vehicle arrangement).

Influence of leaking position

Firstly, a representative hydrogen concentration distribution when the leak is from a vehicle on the lowest level is shown in Fig. 18. The flow of hydrogen leaking backward from the rear of the vehicle shifts immediately upward because of its low density, then rises and gradually collides with pallets or other structures and diffuses. The leaking hydrogen is above the lower flammable limit in a range as high as the pallet, but afterward the concentration thins. The region of diluted hydrogen (0.3 volume %: gray) reaches the emissions louver about 480 sec (8 min) after the start of the leak. The hydrogen flowing out from the emissions louver is proportional to that leaking from the vehicle, and a steady state is reached in about 900 sec (15 min). The region above the lower flammable limit is restricted to a small area immediately behind the hydrogen leak, and to a height of about the distance to the pallet above.
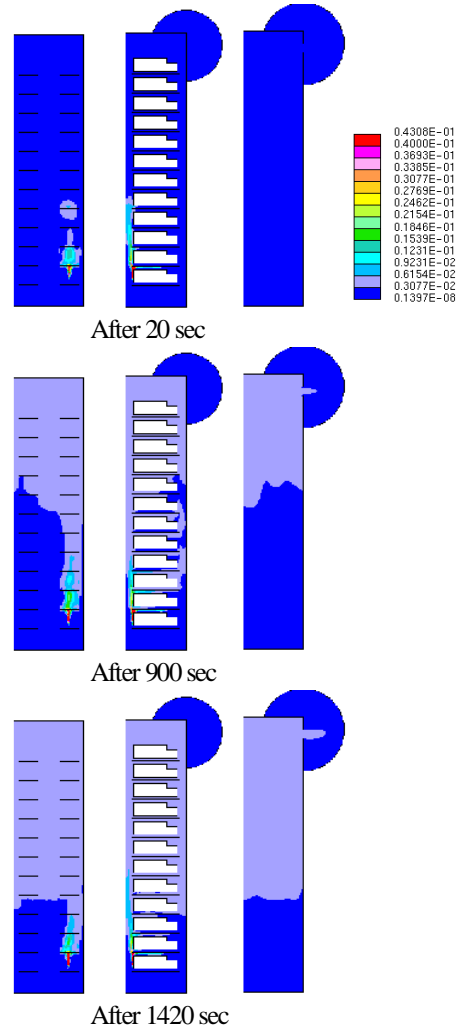

After 20 sec

After 900 sec

After 1420 sec

Figure 18. Hydrogen distribution in multistory parking garage (Case M-1; left: Section A, center: Section B, right: Section C).

Secondly, the hydrogen concentration distribution in the case when the leak is from a vehicle on the second to highest level is shown in Fig. 19. The flow of hydrogen leaking backward from the rear of the vehicle is immediately deflected upward because of its low density. It rises and gradually collides with the pallet or other structure above and disperses. This is the same as in Case M-1. The region of diluted hydrogen (0.3 volume %: gray) reaches the emissions louver about 60 sec (1 min) after the start of the leak. The hydrogen flowing out from the emissions louver is proportional to that leaking from the vehicle, and a steady state is reached in about 600 sec (10 min). The region above the lower flammable limit is restricted as same as Case M-1.
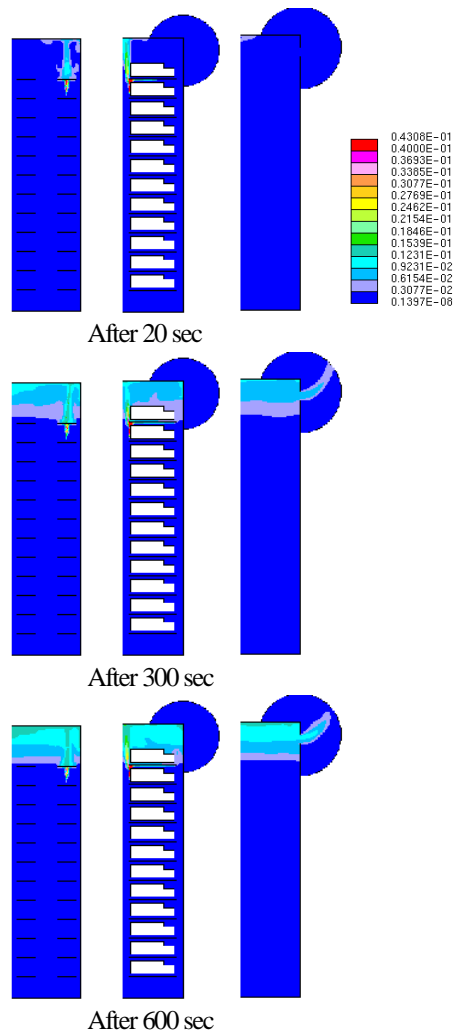

After 20 sec

After 300 sec

After 600 sec

Figure 19.   Hydrogen distribution in multistory parking garage (Case M-2; left: Section A; center, Section B, right, Section C).

Next, the changes with time in the hydrogen concentration at the upper edge of the emissions vent and at the center of the ceiling are shown for Case M-1 and Case M-2 in Fig. 20. The results show that when the hydrogen leak was from the lowest level the hydrogen concentration at the both the ceiling and emissions vent was below 1 %, and even when the leak was from the vehicle on the second to highest level the concentration was lower than 2 %.
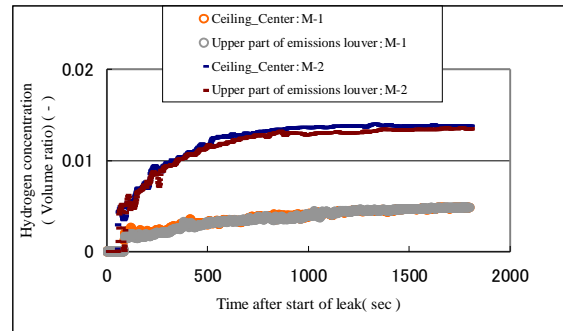

Figure 20. Changes with time in hydrogen concentration at ceiling and emissions vent in multistory parking garage (Cases M-1 and M-2)

<u>Influence of number of leaking vehicle</u>

Figure 21 shows the hydrogen concentration distribution when there is a leak from both the vehicle on the second to top level and that on the bottom level (Case M-3). A small difference was seen in the diluted hydrogen concentration in the section above the highest vehicle pallet between Case M-3 and Case M-2. The diluted hydrogen in Case M-2 was stratified, whereas in Case M-3 the leak from the vehicle on the bottom level gave rise to slight turbulence owing to the gentle flow of dilute hydrogen within the parking garage. However, even in this case the region above the lower flammable limit was restricted to the space between the leaking vehicle and the pallet just above it.

From the above, it thought that when predicting the diffusion of diluted hydrogen within a multistory parking garage, the hydrogen diffusion following a leak can be enough understood from a simulation of a hydrogen leak from 1 vehicle as a parameter of leak position.
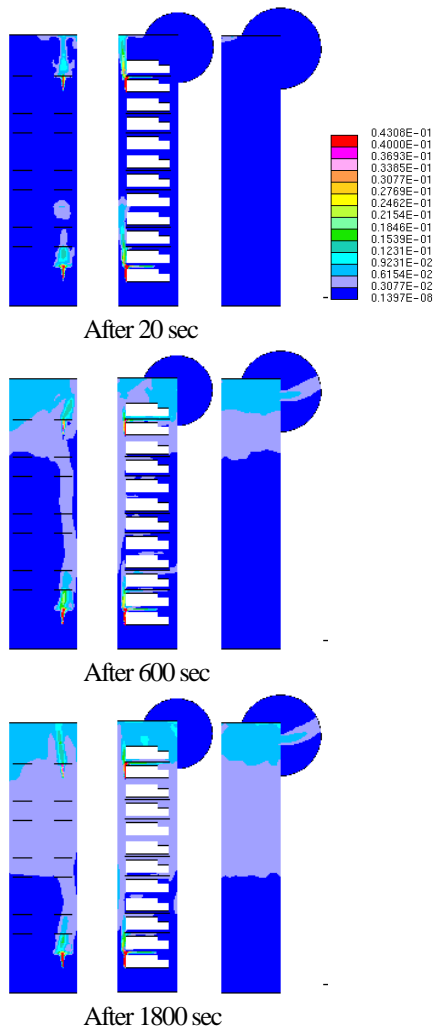
After 20 sec

After 600 sec

After 1800 sec

Figure 21. **Hydrogen distribution in multistory parking garage (Case M-3; left: Section A; center, Section B, right, Section C).**

CONCLUSIONS

Continuous hydrogen leaks from 1 or 2 hydrogen fuel vehicles in large semi-enclosed spaces are not necessarily dangerous if they are at the allowable level for fuel leaks in collisions. This is because the hydrogen above the lower flammable limit is just one restricted area.

The phenomena on leaked hydrogen diffusion in each of the semi-enclosed spaces may be summarized as follows.

Tunnel

In a long tunnel with a rising and downing slope, hydrogen accumulates at below the lower flammable limit along the tunnel ceiling, but in an underwater tunnel there is no accumulation even at the tunnel ceiling. This is because the tunnel longitudinal slope rises toward the tunnel end, promoting the diffusion of hydrogen.

Underground Parking Lot

When air exchange occurs a regulated number of times, the leaked hydrogen is eliminated through the emissions vent. The hydrogen concentration flowing into the emissions vent is already below the lower flammable limit.

When there is no ventilation, hydrogen below the lower flammable limit spreads throughout the parking garage according to the shape of the ceiling.

Multistory Parking Garage

The leaked hydrogen soon diffuses to the pallet just above the vehicle at levels above the lower flammable limit, but afterward falls below the combustion limit.

When the leak is from the bottom level, diluted hydrogen below the lower flammable limit is filled in almost part of the parking garage.

Even when the leak is from the second to highest level, the hydrogen that accumulates at the ceiling is below the lower flammable limit. This is because parking garages are equipped with emissions vents at the top.

ACKNOWLEDGEMENT

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